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DEVELOPMENT AND EXPERIMENTAL RESULTS FROM A 1 kW PROTOTYPE AMR

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ABSTRACT

A novel rotary magnetic refrigeration device has been designed and constructed following the concepts recently outlined in Bahl et al. (2011). The magnet and flow system design allow for almost continuous usage of both the magnetic field and the magnetocaloric material in 24 cassettes, each containing an active magnetic regenerator (AMR) bed. As outlined in Pryds *et al.* (2009) a small scale AMR test device has been used for materials choice and optimising operation, with each component being thoroughly characterised and tested before implementation. The prototype design facilitates easy exchange of the 24 cassettes, allowing the testing of different material amounts and compositions. Operating with 2.8 kg of commercial grade Gd spheres a maximum no-span cooling power of 1010 W and a maximum zero load temperature span of 25.4 K have been achieved. For the purpose of actual operation, simultaneous high span and high performance is required. At a heat load of 200 W a high temperature span of 18.9 K has been obtained, dropping to a span of 13.8 K at the higher heat load value of 400 W.

1. INTRODUCTION

In recent years an increasing number of novel magnetocaloric devices have been designed, constructed and tested. The results and performance continually improve, inching the technology towards the regime of commercial implementation. The exact requirements for such a commercial device of course depend on the niche in which this technology will first break through. Some devices such as chillers or heat pumps require high cooling powers, at modest temperature spans, while others, such as domestic refrigerators or freezers, require high temperature spans but less cooling power. For any application it will be imperative to optimise the device to fit the requirements set out.

1.1. Classification of devices

Traditionally magnetocaloric devices have been classified according to parameters such as the type of magnet (electro- or permanent magnet), morphology of regenerator (particles, spheres, wire meshes or plates) or type of heat transfer fluid (gas or liquid). The classification of devices into two types, rotary and reciprocating, is most consistently reported. However, as this property merely describes the relative motion of the magnet and magnetocaloric material it does not seem to be a defining property of a device. Devices with concentric Halbach type magnet assemblies, see e.g. Tura and Rowe (2011), that are rotated to modulate the field are termed rotary while devices where a single Halbach type magnet assembly is moved back and forth, see e.g. Engelbrecht *et al.* (2009) are termed reciprocating devices. In actual fact two such devices may, except for this difference in the movement of the magnet, be built and operated in identical ways.

The motion of the heat transfer fluid after leaving the regenerator, seems to be a more distinguishing feature. Thus, the use of terms such as “modulating” and “continuous” (or uni-directional) to describe the fluid movement may prove more fundamental. In the modulating type the heat transfer fluid is pushed from the regenerator into the heat exchanger or volume containing the heat load and then the

same fluid is pushed back into the regenerator in the next step of the AMR cycle. The devices presented in Tura and Rowe (2011) and Engelbrecht *et al.* (2009) are both examples of the modulating type. In the continuous type the heat transfer fluid is pumped through the regenerator and passes through the heat exchanger into another regenerator, always in the same direction. This type requires at least two regenerators to which the fluid flow can be controlled. The modulating type of device can either be of the reciprocating type (Zheng *et al.*, 2009) or of the rotary type (Okamura *et al.*, 2006). As the flow in the heat exchange circuit is unidirectional in the continuous type of device, an advantage is that the heat exchangers are not constrained to be directly adjacent to the regenerators, but can be placed some distance from them. In a real device this will be an advantage as it will allow more freedom in the design. Also, the dead volume fluid can be reduced in the continuous type of device, which is very important for the performance. Figure 1 shows two different device designs that could both be called rotary but differ in the sense that (a) would in this classification be termed modulating while (b) would be termed continuous.

1.2. Design strategy

In this paper we discuss the design and results of a device of the “continuous” type, similar to the one in Fig. 1(b). The device concepts have previously been described in Bahl *et al.* 2010. The regenerator consists of 24 separate compartments each operating its own AMR cycle. These are continuously rotated in the cylindrical bore of a concentric quadropole magnet assembly. The eight regions of the magnet (four high field and four low field) each cover equal angular ranges of 45°. The magnet has been built as described in Bjørk *et al.* (2010) in order to maximise the field difference between the high and low field regions. A single pump at the hot end of the device pumps the heat transfer fluid unidirectionally around a circuit, first through a heat exchanger connected to a chiller, into regenerators in the low field regions, into the cold end where heater power is applied by an electric heater, into regenerators in the high field regions and back into the pump. Each opening of the flow circuit into the regenerator cylinder always covers more than one regenerator, so there is a continuous flow in the system, even during rotation.

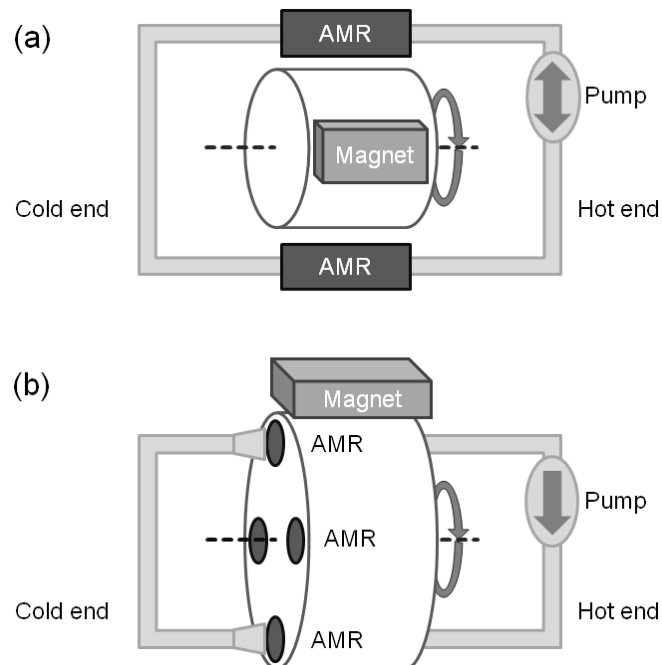


Figure 1. Two types of rotary devices. In (a) a magnet is rotated to magnetise two regenerators in an alternating way. This requires a modulating movement of the heat transfer fluid. In (b) four regenerators are rotated around in the presence of a magnetic field. The stationary flow system feeds the regenerators as they pass the openings. This allows for a uni-directional pump. By making the openings larger and increasing the number of regenerator beds, it is possible to ensure that the flow is always feeding at least one bed.

2. EXPERIMENTAL

The device is designed so that the 24 regenerator cassettes can be removed either as a set or individually. Two such sets of regenerators have been tested in the device. These were packed with two different amounts of Gd spheres from two different suppliers.

The direct operating parameters of the device that can be controlled are the rotational frequency of the regenerators and the fluid flow rate through the circuit. These two combined define the utilisation (see e.g. Nielsen (2011) for definition) of the device. When reporting the frequency, it must of course be remembered that each revolution is equivalent to four AMR cycles due to the symmetry of the magnet. The AMR frequency can be varied in the range 0-10 Hz and the fluid flow can be varied in the range 0-700 l/h, depending on the pressure drop in the regenerators. The heat load applied by an electrical heater is rated to the range 0-1000 W. The hot end inlet temperature is controlled by the output temperature of a large commercial chiller placed in a different room connected to the magnetic refrigeration device through a counter-flow heat exchanger. Thus, measurements are conducted at a fixed chiller temperature, with the hot end inlet being at a slightly higher temperature, depending on the operating conditions, due to heat transfer losses in the heat exchanger. Figure 2 shows a picture of the full system and Figure 3 shows a sketch of the system layout.

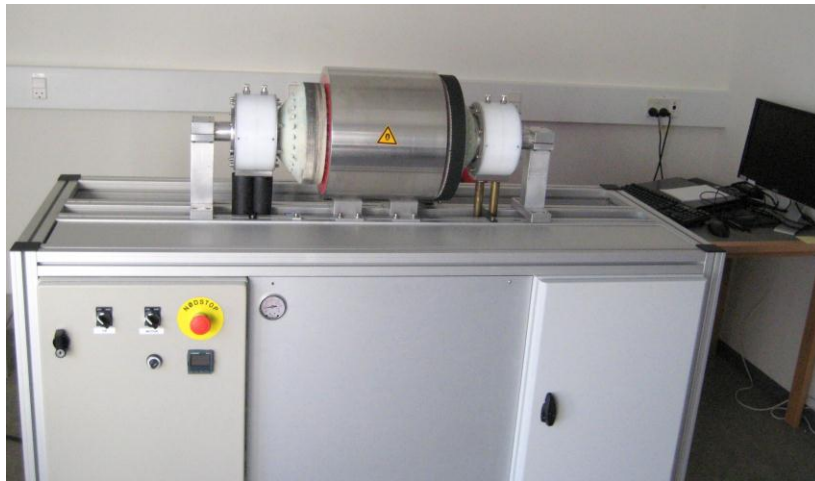


Figure 2. Picture of the system layout in the laboratory.

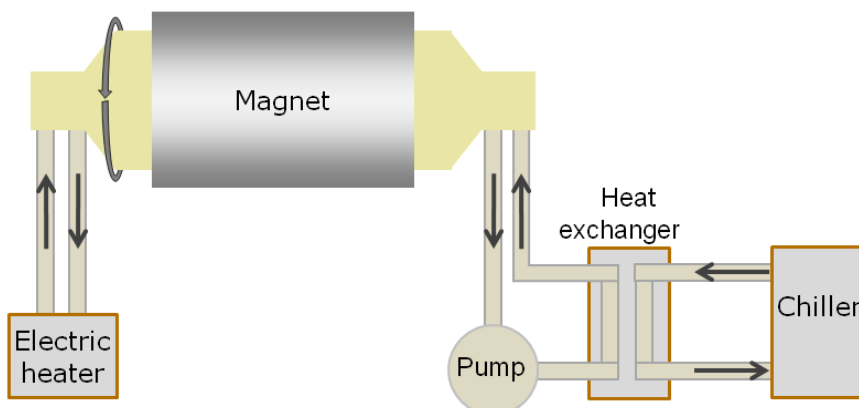


Figure 3. Sketch of the system.

The Gd spheres are tightly packed into nylon cassettes, as the one shown in Figure 4. The Gd spheres are kept in place in a compartment at the centre of the cassette by a fine wire mesh. As seen in Figure 4 there are two flow channels at either end of the cassettes, one for inlet and one for outlet flow. This ensures minimal dead volume and mixing of the hot and cold flows.



Figure 4. One of the regenerator cassette

The first batch of Gd was obtained from Advanced Specialty Metals, Inc., USA. The spheres were in the size range of 0.35-0.85 mm. Measuring isothermal magnetisation curves by Vibrating Sample Magnetometry (VSM) we found a peak ΔS in a 1 T field of $3.5 \text{ J Kg}^{-1} \text{ K}^{-1}$ at a peak temperature of 290.5 K. A total mass of 1.4 kg was used in the 24 regenerator beds.

The second batch of Gd that was tested was obtained from Baotou Rare Earth Institute, China. The spheres were sieved to a size range of 0.25-0.8 mm. By VSM we found the peak ΔS in a 1 T field of $3.2 \text{ J Kg}^{-1} \text{ K}^{-1}$ at a peak temperature of 288 K (Lozano *et al.*, 2012a). A total mass of 2.8 kg was used in the 24 regenerator beds. Figure 5 shows a picture of the second batch of Gd spheres and it is seen that these have, in general, a regular spherical morphology.



Figure 5. Picture of the gadolinium spheres from the second batch. The distance between the lines in the picture is 5 mm.

3. RESULTS

A large number of experiments have been performed on both the batches of Gd in the magnetic refrigeration device. Only a small number of the results from these experiments are presented here, with the focus being on the highest performance of the device. Results from more detailed studies are presented in Engelbrecht *et al.* (2012) and Lozano *et al.* (2012a and 2012b).

3.1. Results from the first batch of Gd spheres

Figure 6 shows results obtained using the first batch of Gd with a total mass of 1.4 kg. All the data is obtained with the chiller set at a fixed temperature of 22 °C, giving hot end temperatures of just above 24 °C. As expected increasing the load on the cold side electric heater to mimic cooling load will decrease the temperature span of the device. It has also been observed that the performance increases with an increased mass flow rate for the range of flows investigated, with the 400 l/h and 600 l/h being the two largest flow rates tested. From experiments where the frequency has been changed a broad maximum in the performance was observed in the range 1.5-2 Hz. Increasing the chiller temperature to 27 °C (giving a hot end temperature of 28.5 °C) gave the maximum recorded temperature span of 16.7 K for this set of regenerators.

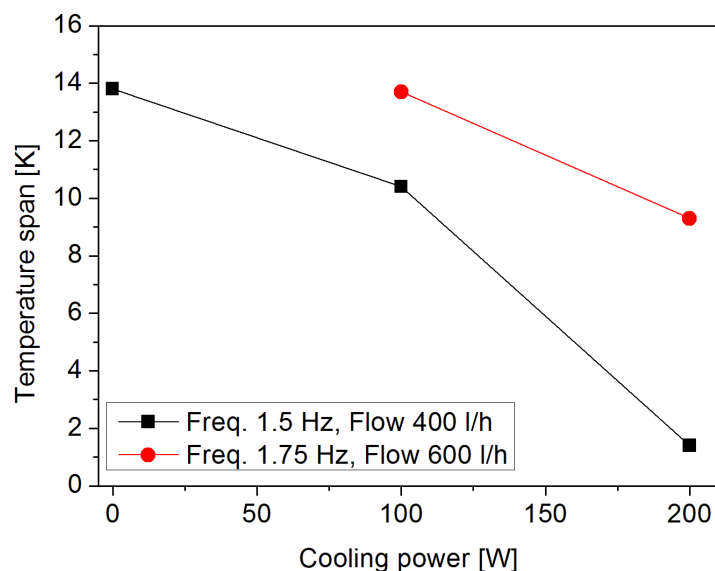


Figure 6. Cooling curves from the first batch of Gd spheres recorded at a hot end inlet temperature of just above 24 °C.

3.2. Results from the second batch of Gd spheres

During the installation of the second set of regenerators containing the second batch of Gd spheres a number of other improvements were made to the device. These upgrades included the installation of a more powerful chiller due to the high cooling powers recorded from the first batch of Gd and even higher cooling powers expected from the larger second batch. Also, the larger amount of Gd in the second batch of regenerators required a more powerful pump in order to overcome the increase in pressure loss. The most important change made was the installation of a new flow control system to manage the timing of the flow into the regenerators. The flow openings, shown schematically in Figure 1(b) as funnels, were made narrower in order to minimise internal leakage in the system.

Figure 7 shows the temperature span as a function of mass flow rate from the second batch of Gd spheres. The AMR frequency was 1.5 Hz and the data was recorded at a chiller temperature of 22 °C, giving hot end temperatures of 24-25 °C depending on the experimental conditions. It is seen that increasing the flow rate increases the performance of the device until saturation is reached at some rate. Again, as expected, an increase of the heat load from 200 W to 400 W will reduce the temperature span. It should be noted that this reduction becomes smaller as the flow rate is increased. Thus, the higher the flow rate the better the device can absorb an applied heater power. This general result has also been observed in other devices. (Tura and Rowe, 2011 and Russek *et al.*, 2010)

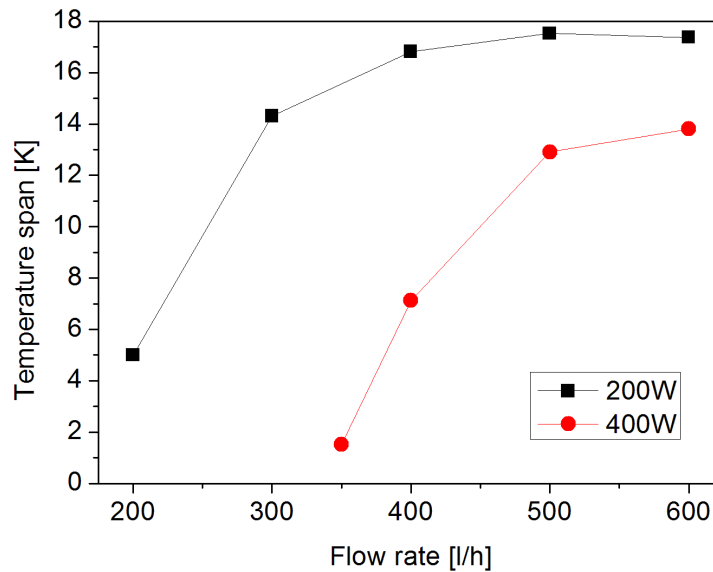


Figure 7. Temperature span as a function of mass flow rate from the second batch of Gd spheres, for heat loads of 200 W and 400 W. The data was recorded at a hot end inlet temperature of 24-25 °C depending on the experimental conditions and an AMR frequency of 1.5 Hz.

Reporting the optimum performance of any device will depend on the intended range of use. Sometimes high temperature spans are required, while at other times higher cooling powers are desired at the expense of the temperature span. Figure 8 shows a selection of the best performances recorded at a number of different cooling powers. It should be noted that each point is obtained at a different frequency, flow rate and chiller temperature and therefore cannot be directly compared. It is noted that the values are quite close to the line connecting the maximum zero load temperature span of 25.4 K (obtained at a frequency of 2 Hz, a flow rate of 400 l/h and a hot end temperature of 28.0 °C) and the maximum zero span load of 1010 W (obtained at a frequency of 1.8 Hz, a flow rate of 680 l/h and a hot end temperature of 19.2 °C). Two noteworthy values in the plot are the span of 18.9 K at a cooling power of 200 W (obtained at a frequency of 2.25 Hz, a flow rate of 500 l/h and a hot end temperature of 24.9 °C) and the span of 13.8 K at a cooling power of 400 W (obtained at a frequency of 1.5 Hz, a flow rate of 600 l/h and a hot end temperature of 24.8 °C).

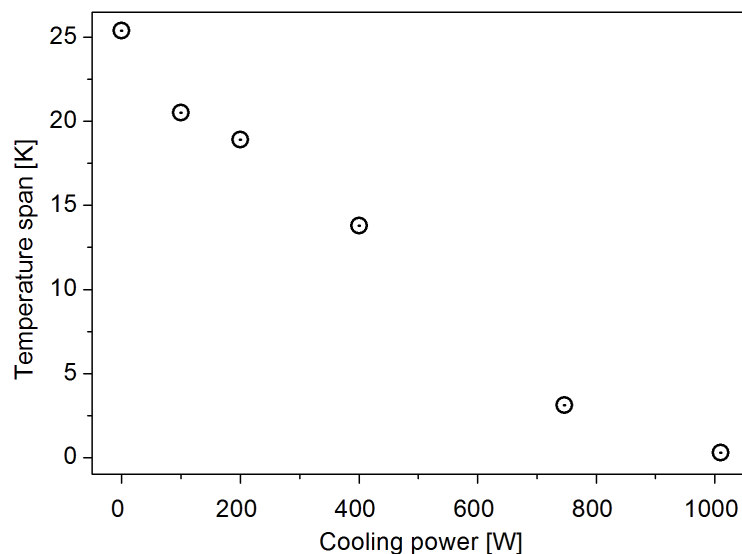


Figure 8. Best performance of the device at different cooling powers. Note that the operating parameters differ for each point in the plot.

4. DISCUSSION

Results have been presented for two different sets of regenerators packed with different amounts of similar Gd spheres. Comparing the performance for identical operation parameters in Figures 6 and 7 it can be seen that the cooling power of the second batch of Gd is significantly larger than for the first batch, due to the larger mass of Gd. This is expected as in general the cooling power will scale with the mass of regenerator material used. The overlapping data for the batches of Gd was recorded at very similar conditions. Linear extrapolation of the cooling curves to zero temperature span gives the mass normalised cooling power per unit mass from the two experiments, see Table 1. It is seen that the values obtained with the two different amounts of Gd compare well with each other, the differences being due to differences in the magnetocaloric effect of the two batches and different temperature spans in the device during the recording of the data giving different parasitic heat loss.

Table 1. Extrapolated zero span cooling power per unit mass at a chiller temperature of 22 °C, frequencies of 1.5-1.75 Hz and flow rates of 400 l/h and 600 l/h.

	400 l/h	600 l/h
Gd - Batch 1	159 W/kg	294 W/kg
Gd - Batch 2	169 W/kg	280 W/kg

The importance of a detailed mapping out of the parameter space is clearly shown. As an example Figure 7 shows how a saturation of the temperature span is reached when the flow rate is increased. Increasing the flow rate further beyond the saturation would only contribute added pump work and would reduce efficiency. However, if the goal is to reach a higher cooling power it may be a good idea to further increase the flow rate as the saturation comes later for higher flow rates. Thus mapping out the parameter space will allow better knowledge of the optimal operating parameters for a desired output. More detailed studies of parameter variations are given in Engelbrecht *et al.* (2012) and Lozano *et al.* (2012a and 2012b). An important tool for the study of AMR devices is numerical modelling as discussed in Nielsen *et al.* (2011). Coupling of the experimental results presented here with numerical modelling will require knowledge of the thermal losses in all system components, including the piping. Such a loss analysis is underway and will allow for accurate modelling of the system. Also, as the system is quite large thermal insulation must be considered.

This work has primarily been concerned with achieving results in the relevant range of temperature spans and cooling powers, not on the optimisation of the size of the device. The seemingly large size is due to the desire to make the device versatile. Being able to exchange regenerators, flow systems etc. is clearly an advantage experimentally, but will of course be at the cost of added volume. The filled volumes of the regenerators tested in the present study were approximately 50 and 100 mm long for batches one and two, respectively. The full length of the bore of the magnet is 250 mm, so only a small part of the magnet is presently used. The magnetic field will decrease close to the ends of the bore (Bjørk *et al.*, 2010), but at least 200 mm could be used. Indeed, it is planned to use stacks of graded ceramic magnetocaloric materials of this length in the device. Recently, high performance has been found in graded materials of the type $\text{La}_{2/3}(\text{Ca},\text{Sr})_{1/3}\text{MnO}_3$ (Bahl *et al.*, 2012) and stacks of these materials are being prepared for a new set of regenerators to be tested in the device. The use of full length stacks will be possible in the device due to the much lower pressure drop over such a stack, compared to that over a container of packed spheres. The importance of comparing the performance of different materials in the same device is discussed in Smith *et al.* (2012).

5. CONCLUSION

High performance, close to the requirements of commercial devices, has been demonstrated on a novel near-continuous magnetic refrigeration device. The device showed a maximum zero span cooling capacity of 1010 W and outstanding temperature spans of 18.9 K and 13.8 K were obtained at cooling

powers of 200 and 400 W, respectively. The versatility of the device allows for exchange of regenerators and two different sets of packed Gd sphere regenerators have been tested.

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